

DESIGN OF A TURBOFAN POWERED REGIONAL TRANSPORT AIRCRAFT

PURDUE UNIVERSITY

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The majority of the market for small commercial transport aircraft is dominated by high-efficiency, propeller-driven aircraft of non-U.S. manufacture. During the past year senior student design teams at Purdue developed and then responded to a Request For Proposal (RFP) for a regional transport aircraft. The RFP development identified promising world markets and their needs. The students responded by designing aircraft with ranges of up to 1500 n.m. and passenger loads of 50 to 90. During the design project, special emphasis was placed upon keeping acquisition cost and direct operating costs at a low level while providing passengers with quality comfort levels. Twelve student teams worked for one semester developing their designs. This report describes several of the more successful designs and those that placed a high premium on innovation. The report also illustrates the depth of detail and analysis in these student efforts.

BACKGROUND: THE REGIONAL AIRLINE INDUSTRY

The Federal Aviation Administration defines the regional transport industry as "those air carriers that provide regularly scheduled passenger service and whose fleets are composed predominantly of aircraft having 60 seats or less." The regional transport industry's primary goal is to provide air transport from small secondary airports to large metropolitan and international airports served by commercial air carriers. The market for aircraft to perform this mission is dominated by high-efficiency, propeller-driven aircraft, with the bulk of the aircraft manufactured by companies outside the United States.

Since airline deregulation began in the late 1970s the differences between regional airlines with small aircraft and larger air carriers have become less distinct. In 1978 regional airlines operated at a level of approximately 49,500 passengers per carrier. By 1988 this average had risen to 180,200, an increase of 205%. This growth of the regional industry outpaced the other parts of the commercial airline industry. The Federal Aviation Administration (FAA) predicts that the number of revenue passenger miles on regional carriers will nearly double between 1988 and the year 2000.

Areas of high growth are likely to be in Europe and Asia, and, to a lesser extent, the United States. However, in the U.S. there is a greater acceptance of the regional airline industry by the public and increasing numbers of commercial partnership agreements, called code-sharing, between small carriers and the major carriers. These agreements are essential to the survival of regional airlines because their financial health is tied to the health of the major airline partner. In 1989, 43 of the 50 largest regional companies participated in code-sharing agreements with major carriers.

The European industry today resembles the U.S. industry immediately after deregulation. European traffic has had recent increases near 17% per year. European airlines have not yet begun the U.S. practice of code-sharing, but it is only a matter of time before this occurs.

In general, world growth of regional traffic, including Asia, is expected to remain healthy and growing into the foreseeable future. The number of new units required to fill demand for new aircraft and replacements for older aircraft has been predicted to be as high as 6000 aircraft through 1998.

On the other hand, problems such as airport congestion have occurred as an increasing amount of air traffic has been scheduled to converge at major hub airports in the United States and in Europe. To ease this crowding, new regional routes have been developed to bypass these hub-spoke combinations. As a result, the regional airlines both serve and compete with major air carriers.

The trend toward hub-bypass and point-to-point regional carrier operation has changed the original mission of regional airlines. This change requires new capabilities from the aircraft serving these missions. These new capabilities either are not met by existing aircraft or are not met efficiently. The current average route length or stage length is 150 to 250 n.m. for regional transport. These shorter routes are served primarily by small capacity, propeller-driven aircraft. Some predictions see the stage length increasing to over 300 n.m. with maximum ranges of over 1000 n.m. required on some routes. In this case, the turbofan engine becomes competitive.

In addition to efficiency, airlines must consider passenger convenience, comfort, and cabin noise levels. Regional airlines (and their passengers) will demand faster, quieter aircraft with more passengers on each flight so that they can serve markets efficiently and competitively. Passengers accustomed to the comfort, speed, and in-flight amenities of major air carriers will come to expect the same attributes on the regional routes. This so-called seamless service between larger carriers and smaller carriers will be a major criterion in the design of new regional aircraft.

Finally, regional airlines must continue to be capable of operating from small community airports. Many of the important smaller airports have runway lengths of as little as 5000 ft. In addition, the smaller communities have stringent noise require-

ments. These FAR 36 noise requirements and the desire to keep passenger cabin noise at low levels will impose important constraints on the designer.

OBJECTIVES

During the past year the mission of 12 Purdue senior student design teams was to develop and respond to a Request For Proposal (RFP) for a regional transport mission. This RFP contained performance requirements chosen by individual teams on the basis of their perception and analysis of the transport market as it will exist in 1995. Special emphasis was placed upon designing to cost, a cost that includes aircraft acquisition cost and operational cost (DOC). Designs incorporating unusual features and creativity were encouraged. The result of this study was not only a perception of what a regional transport should look like, but also an idea of what students thought the most important markets would be.

Although the semester provides a 14-week work schedule, each team had only about 10 weeks to conceive and develop its design concept. The first four weeks of the semester were used to develop market studies and to acquire special design skills such as aircraft weight estimation, design sensitivity techniques, and other traditional techniques.

TEAM REQUIREMENTS

Each design team was subject to stringent analytical, conceptual and reporting requirements for their design. It was required that extensive information on aerodynamic performance be generated together with stability, control, and flying quality information. The structural loads, member layout, and weights and balance information were also required. Coupled with the weights information were the requirements for guarantees that the landing gear could support the ground loads and would meet minimum tip-over and takeoff clearance requirements.

The ability to perform the required transport mission from takeoff to cruise to landing with required reserves was rigorously checked using analytical procedures that ranged from highly preliminary to extremely sophisticated. These checks used class-developed performance computer codes and, in many cases, the Flight Performance and Optimization (FLOPS) code developed by NASA/Langley and modified at Purdue for use on the personal computer. To obtain performance data it was necessary to have extensive engine data. Such data is usually a closely held secret of engine manufacturers.

To remedy the problem of obtaining accurate engine data, two personal computer codes, ONX and OFFX, were used. These codes can match and generate crucial engine performance data such as fuel flow at various Mach numbers, altitudes and power settings. These codes were used extensively by the USRA Teaching Assistant during the summer of 1990 and a videotape and set of assignments were formulated for class use.

These codes were used to modify the engine cycle and inlet temperatures as required to meet the specific missions of the design team aircraft. In some cases this required extensive redesign of the three engine designs that the students were given at the beginning of the class.

The final result of each team's work was a detailed, 100-page design report, an executive summary of this report, and a 25-page mid-term report that was evaluated by a team of technical writing experts from the Thiokol Corporation. What follows is a summary of some of the data presented in these reports.

THE VALUE OF TIME AND THE COST OF SPEED

Time is money. Time is of value to a passenger on a regional transport, but it also costs money to acquire the speed necessary to save time. This cost is reflected in all of the empirical relations used to estimate aircraft cost.

Figure 1 shows the amount of time required to complete a trip as a function of airspeed. This so-called timescoping analysis shows a knee in the curve. At Mach numbers or airspeeds above this knee, there is very little change in the trip time as Mach number increases. In general, the knee moves right to larger airspeeds when the range of the aircraft increases. For short-range aircraft, it is not important that the aircraft be extremely fast.

Because of the market factors that governed each group's design, the 12 teams independently arrived at the conclusion that it was unnecessary to have the aircraft travel extremely fast. In addition, because aircraft acquisition cost increases with cruise Mach number, cruise speeds were kept down so that they ranged from Mach 0.70 to 0.82. These cruise Mach numbers can be compared to longer range aircraft that may cruise up to Mach 0.90.

PASSENGER LOADS, RANGE, AND REQUIREMENTS

Recent trends in the regional transport business have been directed toward development of aircraft with up to 100 seats and ranges up to 1500 n.m. As a result, the RFPs developed by the 12 design teams displayed a wide range of seating and range objectives. Figure 2 shows this data for the 12 design groups and compares it to two other aircraft now in service.

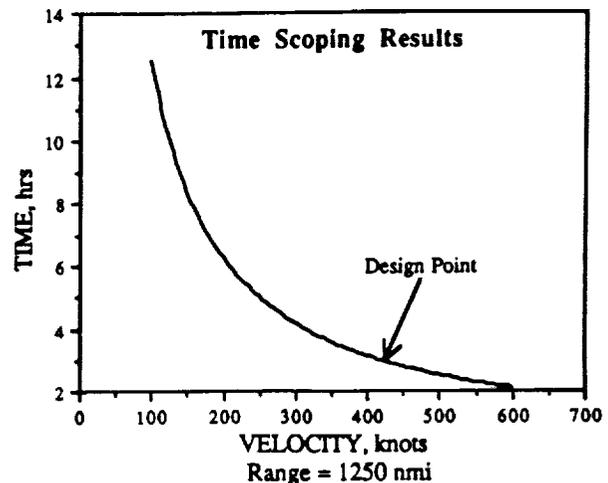


Fig. 1. Trip time vs. airspeed.

The smallest aircraft developed at Purdue has a passenger capacity of only 50 with a range of 800 to 900 n.m. (with reserves). The largest aircraft is designed to hold 90 passengers and had a range of 1650 n.m., comparable to the Fokker 100.

Design groups identified the European and Asian markets as being more promising than the U.S. market. As a result, while they used FAR standards in their work, design teams also used the Association of European Airlines Requirements (AEA) as a standard.

While the AEA standards repeat many of the FAR requirements for safety, they also set minimum standards for passenger comfort in terms of such items as seat pitch. All 12 aircraft meet these AEA standards and use AEA guidelines to calculate DOC. Let us now consider some of the designs generated by the design teams and their features. Note that all of these designs are required to carry a cockpit crew of two.

THE WAG-78

The WAG-78 is a 78-passenger aircraft with a range of 1100 n.m. It is designed to cruise at $M = 0.80$ at 35,000 ft with an operational ceiling of 39,000 ft. The aircraft will take off from a runway longer than 5500 ft on a standard day in Denver. This design is a modification of a design that has appeared during the past ten years and is shown in Fig. 3.

The WAG-78 provides an example of a departure from conventional subsonic aircraft design because it uses the joined wing concept developed several years ago. This joined wing has a rear wing surface that acts both as a horizontal tail and as an external strut to stiffen and strengthen the wing. The takeoff gross weight (TOGW) of this aircraft is 54,900 lb with an empty weight of 30,500 lb. Some weight savings were achieved because of the joined wing structural design.

The WAG-78, like all the other student designs, was powered by a redesigned General Electric TF 34 engine. This engine was resized and slightly redesigned to develop a thrust of 11,900 lb.

Two engines were used for this design to satisfy one engine inoperative (OEI) requirements and so that the engines would be capable of developing thrust levels sufficient to meet the takeoff requirements and OEI criteria. The thrust-to-weight ratio for this aircraft is rather large so that the aircraft can climb rapidly to its cruise altitude.

The designers of the WAG-78 were conservative in their estimates of the number of aircraft that they could market. They predicted that they would be able to sell 175 aircraft over an 11 year development and production cycle. This number did not include the 5 test aircraft that they chose for a development phase that was to last 3 to 5 years. This unusually large number of test aircraft were thought to be necessary because of the new joined-wing design feature that they proposed to use.

The WAG-78 designers estimated a development and testing cost of \$810 million and production costs of \$2.262 billion. A cash bucket analysis shown in Fig. 4 was used to estimate the price of this aircraft to be \$20 million if the cost of capital is 18%. Operating costs for an 1100-n.m. trip were estimated at \$2060 to give a low 3.6 cents per revenue seat mile assuming a 66.7% load factor.

The WAG-78 design team compared their design to the BAE 146-100 and the DeHaviland Dash 8-400 and found that the

Design Teams' Market Profile

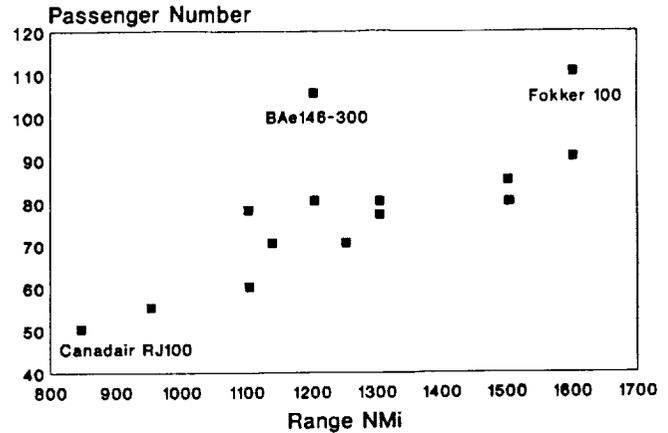


Fig. 2. Design team passenger number vs. range.

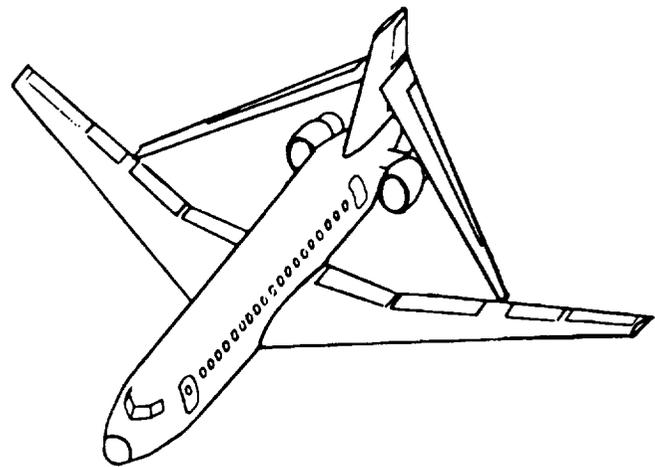


Fig. 3. WAG-78 Joined Wing Design.

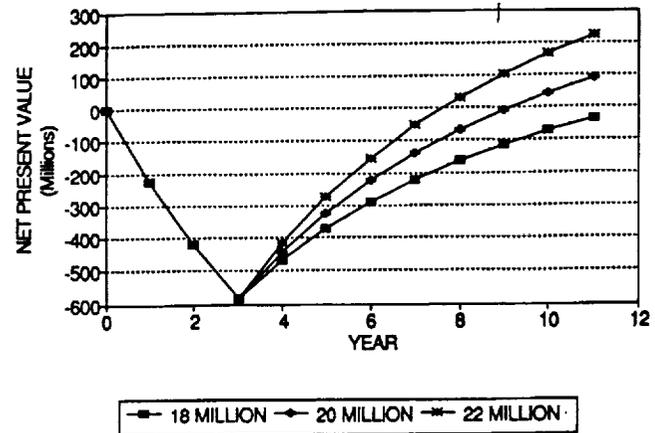


Fig. 4. Cash Bucket Price Analysis.

WAG-78 cost 0.5 to 1 million dollars more than these aircraft. On the other hand, it could be operated at a seat mile cost of about 10% less than the BAe 146-100 and only slightly more than the Dash 8. The Dash 8 is a turboprop aircraft and, in its latest stretched version, its range has been reduced to 800 n.m. at a speed of 350 knots.

THE ARCA-60

Design reviews with industrial representatives were held during both semesters of design team activity. Design representatives included a marketing authority, a propulsion and maintenance expert, and an airline pilot. The airlines represented included Southwest Airlines, USAir and Northwest Airlines.

In all cases, the teams were encouraged to simplify their designs and to consider flight operations and maintenance. While this advice was valuable, it also tended to discourage configuration innovation. As a result, aircraft external features evolved to become somewhat traditional.

An excellent example of a well-conceived, traditional, DC-9-like design is the ARCA-60, shown in Fig. 5. This aircraft has seating for 60 passengers with an 1100-mile range and enough fuel to fly to an alternate airport 200 n.m. away and hold for 30 minutes. It has a maximum Mach number of 0.80 and cruises at 35,000 feet at $M = 0.75$.

Extensive studies were done by the ARCA-60 aerodynamicist to obtain an efficient airfoil shape for low drag. These efforts led to the choice of a NASA supercritical airfoil, the SC(2)-0412. An Euler code analysis of the section estimated the drag divergence Mach number of this section to be 0.75. This code was used to accurately model the nonlinearities that occur in transonic flow.

The ARCA-60 wing was mounted low on the fuselage to allow for aft mounting of the engines and easy storage of the landing gear. Aft mounting of the engines resulted in the requirement

for a T-tail design. Although the c.g. movement during flight is minimal, the ARCA-60 requires a large tail volume to rotate the nose on takeoff from short runways. The extra cruise drag from this configuration was regarded by the design team to be acceptable.

The ARCA-60 has a predicted TOGW of 60,300 lb and a wing loading of 75 psf at takeoff. The wing quarter chord sweep is 20.4° to help reduce torsional loads while maintaining aerodynamic efficiency. After extensive analysis, a taper ratio of 0.2 was chosen so that the lift distribution approached that of a minimum drag, elliptical spanwise lift distribution.

The thrust per engine was 9650 lb and is much lower than the WAG-78. With engine cost estimated at \$2.4 million per aircraft, the ARCA-60 is estimated to cost \$19 million. This number is based on a production run of 300 and a cost of capital of 10%. This latter cost is low compared to the 18% estimate of the WAG-78 team. The ARCA-60 program is estimated to last for 20 years and to produce a profit of \$819 million.

As shown in Fig. 6, the cabin cross-section is designed for comfort. This feature is also present in the other 11 designs.

THE SRT-80 AIRCRAFT

The SRT-80 design, shown in Fig. 7, is representative of several designs produced during the project (note that this image is produced by a mesh generation program and some distortion in engine placement will occur when the computer screen image is printed). This aircraft resembles the 737/757 class of aircraft with wing-mounted engines. This aircraft can cruise at Mach 0.80 and carries 80 passengers a distance of 1200 n.m. with reserves. It has a wing loading of 55 psf to allow it to take off from 5500-ft runways at 2000 ft above sea level.

The aircraft has a span of 94 ft and a length of 93 ft. The wing itself has a dihedral angle of 5° for stability. At a design

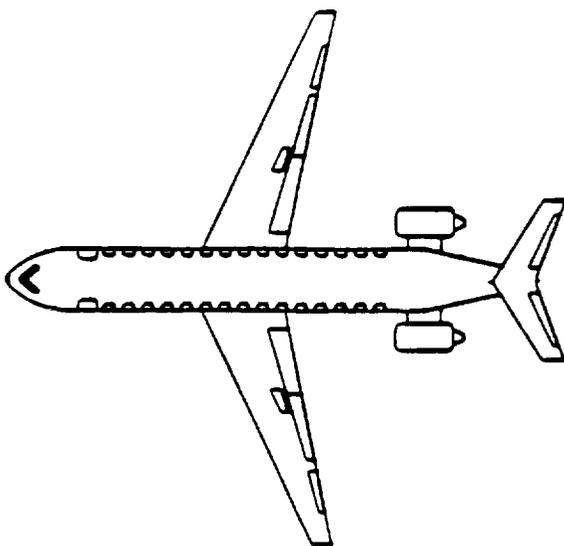


Fig. 5. The ARCA-60 Aircraft.

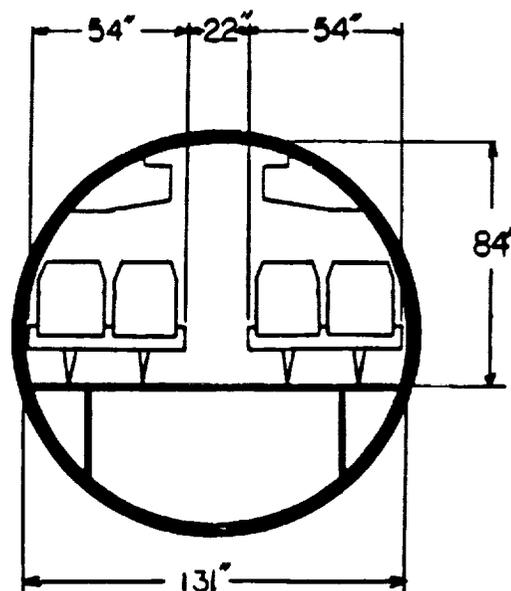


Fig. 6. Cabin Cross-section.

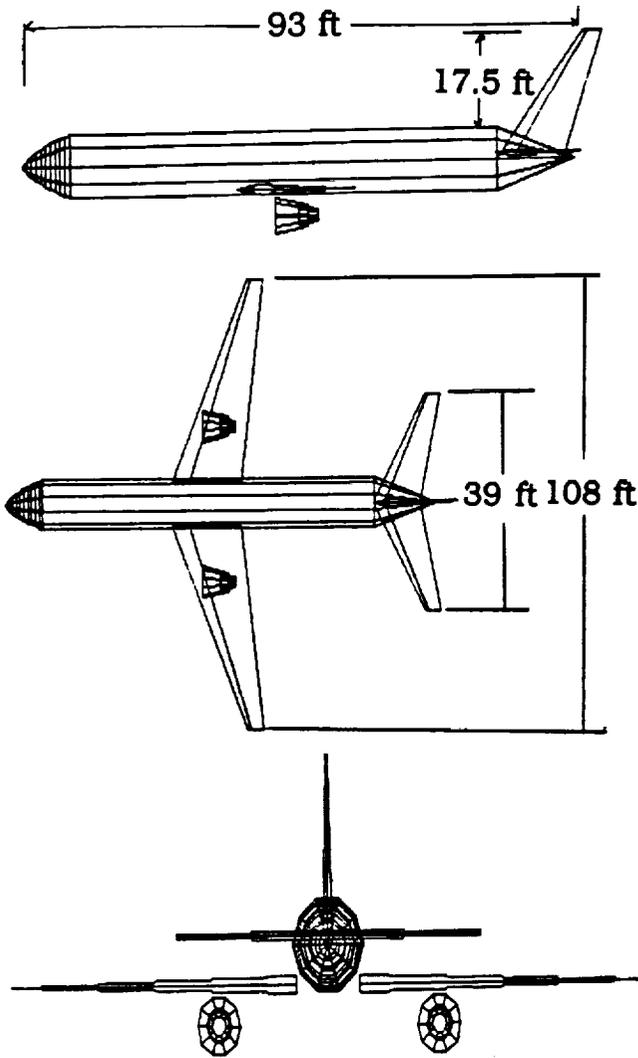


Fig. 7. The SRT-80.

TOGW of 60,900 lb this aircraft will use 9400 lb of fuel to complete its mission. The engines on the SRT-80 are designed so that the integrated airframe and propulsion units will generate 101 seat miles (n.m.) per gallon of fuel.

The engines are modified versions of the GE TF 34 turbofan design. They were scaled up to increase the thrust from each engine. The TF 34 was selected by the SRT-80 team because of its superior fuel efficiency. The propulsion specialist increased the bypass ratio from 6.23 to 7.0 to increase thrust by almost 7% and to decrease fuel consumption by over 4%.

Like most of the designs, the structure of the SRT-80 is composed primarily of aluminum, with small amounts of composites used in non-load-bearing structure. The structure is estimated to be 40.1% of the TOGW. Passengers and baggage are an additional 31.6% while the systems and equipment are 3.3%. The remaining weight is due to passengers and their baggage.

THE WOMBAT

The last airplane to be reviewed is a blend of conventional design with a few unconventional features. This design, shown in Fig. 8, began as a design that closely resembled the BAe-146 or the C141. The high wing was judged by the designers to be desirable because of its handling qualities during the landing in ground effect. Wing mounted engines were used for ease of access. Landing gear is stowed in a blister pod in the fuselage and meets tip-over criteria.

The Wombat has a wing span of 92.2 ft, a length of 105 ft and weighs 66,950 lb to give it a wing loading of 89 psf at takeoff. The Wombat is designed to carry 70 passengers, but will also be available in a stretch version that will carry 100 passengers. The projected cost is \$22 million.

The design team became concerned about cabin noise from the engines and overhead hydraulic lines as well as the potential for blade damage from an engine failure in flight. As a result, they moved the wing back instead of attaching the engines to the fuselage as a number of other design teams had done. This necessitated the addition of a canard to raise the nose at takeoff. It also generated concern for the effects of the canard tip vortices on the engine intakes.

The aerodynamicist and the stability and control specialist cooperated to place the wing and canard properly to reduce trim drag in flight. The result was an optimized three-lifting-surface aircraft shown in Fig. 8.

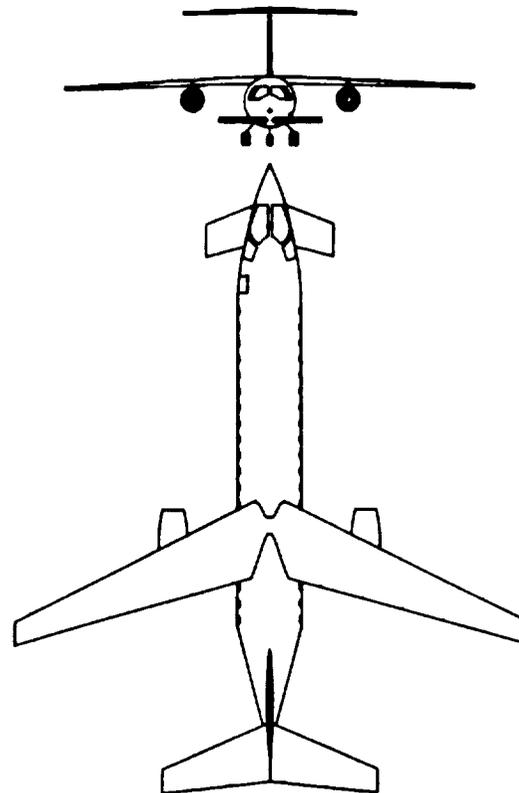


Fig. 8. The Wombat (note difference in scales).

The fuselage of this aircraft is to be constructed of Arall. This composite material has an organic fiber material sandwiched between layers of aluminum. This material should be safer and deaden sound from the engines better than conventional aluminum.

CONCLUSION

The Purdue design class considered the engineering/economic task of designing a regional transport aircraft with turbofan engines. Market considerations drove this design to passenger capabilities of about 70 passengers. As a result, one of the three available engines, the GE TF 34, was the clear choice of the 12 teams that participated.

One agreement among the design teams was that the regional transport market would grow. As a result, a successful design will have a good chance of returning a profit to its investors. Because of the emphasis placed upon practicality and economy, most aircraft have a conventional appearance. In addition, most aircraft use minimal amounts of composite materials for construction and have conventional controls. On the other hand, all groups embraced supercritical airfoil technology.

The emphasis upon cost and price of the aircraft required a model to predict these numbers. The teams developed such models and the ability to judge the desirability of trading one technology against another. In the long run, it is the clear relationship between market forces and engineering decisions that will prove to be the most valuable aspect of this design experience.